Thermal ionization mass spectrometer U-Th dates on Pleistocene speleothems from Victoria Cave, North Yorkshire, UK: Implications for paleoenvironment and stratigraphy over multiple glacial cycles

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ABSTRACT

We present 23 new thermal ionization mass spectrometric U-Th dates for Victoria Cave, North Yorkshire, UK. Victoria Cave underwent repeated glaciation during the late Pleistocene and contains one of the longest Quaternary cave sequences in Britain. The dates reveal that speleothem formation began beyond the range of the dating technique (before 600 ka). Finite reproducible dates of 490 –9/+10 ka confirm speleothem deposition during marine isotope stage (MIS) 13, the oldest date we know of for this part of Britain. Further speleothem formation was dated to MIS 11, MIS 9, MIS 7, and MIS 5. The results are the basis for a new chronology of Quaternary events for the cave and greatly enhance our understanding of the factors affecting the formation of the sedimentary sequence. Cyclical climatic and environmental change throughout the late Pleistocene triggered cyclical sedimentation events in the cave. All the interglacial periods show calcite deposition but with growth phases postdating the warmest events of MIS 11 and MIS 5e. The position of the cave halfway up the side of a glacial trough resulted in very distinctive sediment during the more extreme glacial maxima: ice-dammed lakes formed inside the cave and deposited varve-like clay rhythmites. The dates inferred for these deposits suggest that this locality underwent significant glaciation during MIS 12, MIS 10, MIS 6, and MIS 2, and that the ice was warm based. The absence of rhythmites during MIS 8 suggests minimal ice cover at that time. This is the most complete record for glacial events in the region; it is the only site where successive glacial maxima can be identified and dated. The record of large faunal remains indicates that the cave was open to the surface, only for relatively short times, during MIS 13, MIS 12, MIS 5e, the Late Glacial Interstadial, and parts of the Holocene. It is inferred that at other times the cave was closed because scree formation blocked the entrance. The record of vertebrate remains is therefore controlled by geomorphological processes. The deteriorating state of this unprotected site remains a cause for concern.

INTRODUCTION

Victoria Cave (North Yorkshire) contains one of the longest sequences of Quaternary cave sediments in Britain. The site underwent large-scale excavations in the 1870s and the reanalysis of archived material from these investigations and later work in the 1930s has produced internationally significant results: first, alpha-spectrometric (AS) and thermal ionization mass spectrometric (TIMS) dates for speleothems that had formed on top of large mammal bones, including hippopotamus (*Hippopotamus amphibius*), provided terrestrial dating evidence for the Last Interglacial, stage 5e in the marine isotope record (Gascoyne et al., 1981; Gilmour et al., 2007); and second, accelerator mass spectrometry (AMS) radiocarbon dating for Late Glacial bones and artifacts showed that the first people colonizing northwest Europe after the Last Glacial Maximum (LGM) reached the north of England during the early part of the Late Glacial Interstadial GI 1e in the Greenland ice core record (Jacobi et al., 2009). However, these key biostratigraphic units in the cave are part of a much longer sequence of clastic sediments and speleothems that reveal evidence for cyclical deposition over multiple glacial-interglacial climate cycles. Although unique in terms of a cave record, these sediments are hardly known other than in the preliminary interpretations make by the geologist Richard Tiddeman in the 1870s (Tiddeman, 1872a, 1872b, 1873, 1875, 1876a, 1876b, 1877, 1878a, 1878b, 1879). We use here TIMS dating of speleothems to provide a more precise and more extensive chronology than has formerly been possible. We also demonstrate the scientific value of historic documents in providing otherwise unattainable information about an important early cave excavation (O'Connor, 2007). The description we present here represents the first attempt at a modern reinterpretation of this unique cave sequence.

Victoria Cave's interest to archaeologists and Quaternary scientists is reflected in its conservation status under British legislation; it is

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a designated Scheduled Ancient Monument (SAM) and a Site of Special Scientific Interest (SSSI). The cave (Ordnance Survey Grid Reference: SD838650 2°14.9′W, 54°04.8′N) is at an altitude of 440 m above Ordnance Datum (OD) on the limestone uplands northeast of Settle, North Yorkshire, UK (Fig. 1). It is developed in massive, gently dipping beds of Goredale limestone of Carboniferous age (Mundy and Lord, 1982). The phreatic cave remnant is now exposed in the steep, scree-mantled slope of the glacial valley side. The well-bedded rock in the cliff above the cave is a ready source for scree, while inside the cave bedding-plane collapse forms large roof fall blocks. The cave has clearly been truncated by glacial erosion, evidence of which can be seen in the remnants of phreatic features now outside the cave and partly covered by LGM diamict (Fig. 2).

Large-scale excavations in the 1870s revealed a deep sequence of Quaternary cave sediments, including bone layers and clastic and speleothem deposits. The cave is one of the most northern caves in Britain with such a long sequence of deposits that is within the known limits of the Devensian glaciation (marine isotope stage, MIS 2). Figure 1 shows the location in relation to the Devensian and Anglian (MIS 12) glacial limits and to other important Quaternary sites. The excavations, from 1870 to 1878, were based on early scientific methods developed by William Pengelly at Kents Cavern, Devon (Pengelly, 1869, 1884; McFarlane and Lundberg, 2005). The excavation was directed first by William Boyd Dawkins from 1870 to 1873, and then by Richard Tiddeman from 1874 until 1878 (Dawkins, 1871, 1874; Dawkins and Tiddeman, 1873; Tiddeman, 1872a, 1872b, 1873, 1875, 1876a, 1876b, 1877, 1878a, 1878b, 1879). These investigations aimed to find bone deposits inside the cave that were older than the last ice advance, indicated by the abundant evidence in the region for glacial activity (Tiddeman, 1872b), and in the process, Tiddeman described the sediments. Initially he designated three main units: the "Upper Cave Earth" containing the Late Glacial bone bed and Holocene material; the "Laminated Clay" (later changed to "Upper Laminated Clay"); and the "Lower Cave Earth," which contained the Hyaena Bone Bed. As the excavations progressed more deeply, Tiddeman reported further deposits of laminated clays and speleothems, termed collectively the "Lower Laminated Clays." The upper units can be traced in the Entrance Series and into the cave interior, but the accounts of the "Lower Laminated Clay" are very confusing.

In 1937 examination of previously unexcavated areas at the back of the cave recovered faunal remains of the Hyaena Bone Bed encrusted

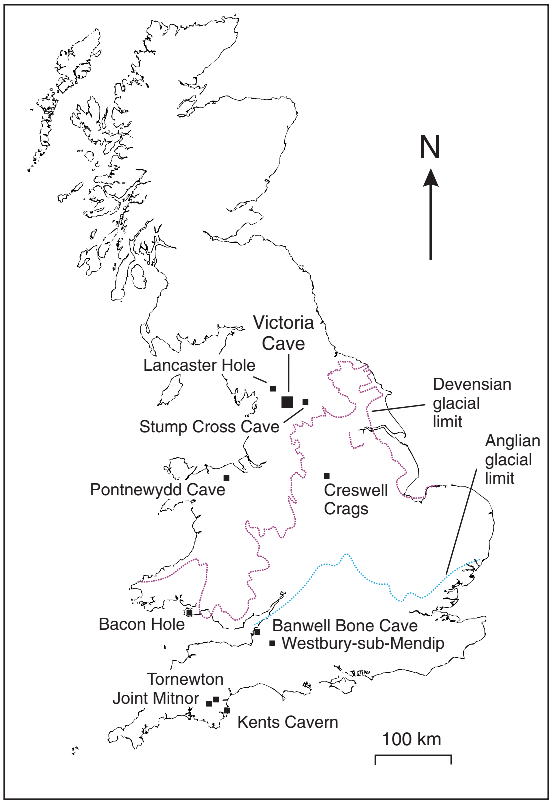


Figure 1. Location of Victoria Cave in relation to the southern limit of Devensian (marine isotope stage, MIS 2) ice, the southern limit of Anglian (MIS 12) ice (glacial limits compiled from Bowen, 1999; Bowen et al., 2002; Evans et al., 2005), and some of the important Quaternary sites.

Figure 2. An 1873 view of the early stages of the excavation of Victoria Cave showing phreatic features in the relict cave wall outside the cave (right side of image) that had been exposed by glacial backcutting of the cliff line. The well-jointed and bedded rock provides ample material for the large scree that almost blocked the cave entrance, and the massive fallen roof blocks inside the cave (two of the people are sitting on one of the blocks). At this stage of the excavations, the glacial diamict that underlies the scree is just coming into view to the left of the large upright wooden scale bar.

by speleothem deposits. In the 1970s the cave was the focus for a program of AS U-Th speleothem dating (Gascoyne, 1977, 1980; Gascoyne et al., 1981, 1983a, 1983b; Gascoyne and Ford, 1984). Although the results were limited by the precision and range of available techniques, this study provided the first direct ages for the last interglacial (MIS 5e) bone bed. It also recognized several earlier phases of speleothem formation, the oldest of which were found to be beyond the upper age limit of the speleothem dating technique at that time (350 k.y.). Many of the samples were dated to the period 310–180 ka (MIS 7–9) and Gascoyne (1980, 1992) focused on one of these for detailed dating and isotopic study. Gascoyne et al. (1983a, 1983b) and Gascoyne and Ford (1984) used the Victoria Cave dates as part of a metastudy of the relationship between landform development, speleothem growth, and climate. Gascoyne's focus was not the sediments, and he largely relied on the sedimentary interpretations from Tiddeman, as have all the publications since (e.g., Murphy and Lord, 2003; Lord et al., 2007). Essentially the sedimentary sequence has not been revised since the earliest work.

For this new study we revisited the site, U-Th dated by TIMS many of the older archived materials, and collected two new samples. We had three main aims: (1) to redate all of the important calcite horizons, especially those that were either close to the limit, or beyond the range, of alpha dating; (2) to revisit the sedimentological and stratigraphic relations in the field; and (3) to review the written documentation from the original field notes of the 1870s excavations. We are now able to report finite ages on all except one of the formerly undatable samples and a new record for the age of cave deposits in the region. The dates provide a framework around which we can reconstruct mid- to late Pleistocene events in the cave (and by implication the region). This new reconstruction is also based on a comprehensive reexamination of the extensive collections and paper archives surviving from the 1870s work and the excavation in 1937. It represents our best understanding of the literature, the most important being Tiddeman's reports (from 1873 to 1879), and including the unpublished cave excavation records kept by J. Jackson (1870 and 1875–1878; these are handwritten excavation registers, kept in the private collection of T.C. Lord), the site superintendent during the 1870s excavations; the unpublished records of T. Lord (a 1937 handwritten manuscript concerning excavations in Victoria Cave, including photographs, kept in the private collection of T.C. Lord); the AS dates from Gascoyne's studies (Gascoyne, 1992; see also Gascoyne and Ford, 1984); our TIMS dates; and our observations of deposits still exposed in the cave.

METHODS

Sampling

In the field it is now difficult to see the details of the original sedimentary sequences. The earlier excavations have removed much material and the wreckage now obscures much of what is left. In addition, damage to the sediments is ongoing from human and animal activities. The status of the site as a SAM and SSSI limits the amount of field scientific research that can be carried out. Therefore, following the example of Gascoyne et al. (1981) and Lord et al. (2007), of using archival material in favor of the less environmentally destructive practice of fresh sampling, we first focused on redating as much archival material as possible. The remains of the samples documented in Gascoyne and Ford (1984) are now archived in the School of Geography and Geology, McMaster University, Hamilton, Canada. The remains of the MIS 5e bone bed material excavated in 1937 (Gascoyne et al., 1981; Gilmour et al., 2007) are in the private collection of T.C. Lord.

Of the seven of Gascoyne's samples that were beyond the range of alpha dating (Gascoyne and Ford, 1984), we have found remains of 76155, 79155, 77237, and 76151 (see Fig. 3 for sample locations). We found nothing from 77238B, 77150B, or 77230, but these pieces were not critical to understanding the sedimentary sequence. Because of its importance in the sequence, one of the oldest pieces underlying the clays, the equivalent of Gascoyne's 77238B, has been resampled (with permission from Natural England and with minimal impact on the cave): this is our sample 63272. We also sampled VC09/1, an extensive ~7-cm-thick, "dirty" (i.e., contaminated with detritus) flowstone from directly underneath the large roof fall block in the Mid-Cave Series that had never before been described or sampled. This flowstone is not the typical white calcite that stands out among the clays; nevertheless, it is surprising that it had not been remarked upon by Tiddeman or Gascoyne.

Of the samples within the range of alpha dating, but considered to be especially significant to the sedimentary sequence, we were able to recover some of 77151 (judged by Gascoyne and Ford, 1984, p. 80, as the "most important Victoria Cave speleothem" because they used it for a detailed isotopic profile), but, unfortunately, not the basal piece, which would have been most interesting for TIMS dates. We found material from 79150, but not much of the basal part, and a search in the cave also failed to turn up any equivalent material. We had hoped to find 77159 because it was reported as having four layers of calcite separated by detrital layers, but did not. We dated VCB, from the collection of T.C. Lord, a piece of flowstone overlying the "Last Interglacial bone bed."

Dating

Each sample was sectioned, polished, and scanned. For each TIMS date, 1–1.5 g of material was sliced parallel to the growth layers. Each subsample for dating was examined under binocular microscope and any visible detrital particle, vug, or crack was excavated using a dentist's drill under the microscope. Samples were dated and analyzed by standard U-Th disequilibrium techniques (e.g., Ivanovich et al., 1992, Chen et al., 1992). All chemical preparation was done in ultraclean conditions. Samples were ultrasonically cleaned, heated for 5 h at 875 °C to remove organics, dissolved in HNO_3, and spiked with ^{233}U-^{236}U-^{229}Th tracer (calibrated by analysis of uraninite in secular equilibrium). U and Th were coprecipitated with iron hydroxide, and purified twice on anion exchange columns (Dowex AG1-X 200–400 mesh). Measurement of U and Th isotopic ratios was done using the Triton TIMS at the Isotope Geochemistry and Geochronology Research Centre, Carleton University, Ottawa, Ontario. The average 2σ error of $^{234}U/^{238}U$ is 0.09% and of $^{230}Th/^{234}U$ is 0.19% (instrumental reproducibility is 0.06% for $^{234}U/^{238}U$ and 0.11% for $^{230}Th/^{234}U$). The precision on the resultant ages varies with age from ~0.5% on the youngest to ~3% for the oldest. All ages were adjusted for detrital contamination using the typical silicate activity ratio $^{230}Th/^{232}Th$ of 0.83 ± 0.42, derived from $^{232}Th/^{238}U$ activity ratio of 1.21 ± 0.6, $^{230}Th/^{238}U$ activity ratio of 1.0 ± 0.1, and $^{234}U/^{238}U$ activity ratio of 1.0 ± 0.1 (following Cruz et al., 2005). In all cases except for VC09/1, the visibly dirty sample, the adjusted ages are within error of the raw ages.

RESULTS

Samples and the TIMS Dates

Data from the TIMS analyses are shown in Table 1. All errors are 2σ. The sample locations and their sedimentological contexts are shown in Figure 3. The samples are shown in Figure 4 and described in the following.

Sample 76155 is a thin, two-layered flowstone wall veneer overlying mud, collected by Gascoyne from inside the steeply inclined rift on eastern side of Chamber D. It was outside the range of alpha dating. Both TIMS dates, on the upper layer and the lower layer, were older than 600 ka, the better run giving a lower range of 580 ka in MIS 15 (and an upper range

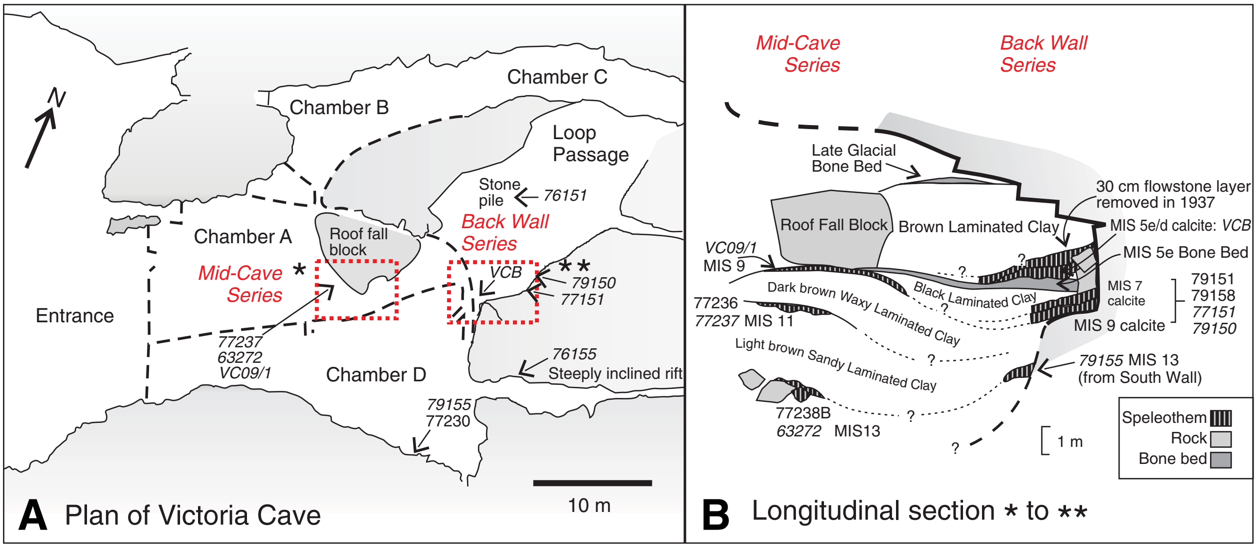


Figure 3. A. Simplified plan of cave. The original chamber delineations (the approximate position shown by the dashed lines) were apparent when the floor was still full of sediment. In the post-excavation cave, the separation into chambers is no longer apparent. The main sections studied, the Mid-Cave Series and Back Wall Series, are shown as dotted rectangles. The numbers represent samples from Gascoyne's (1977, 1980, 1992) study (discussed in the text) and the new thermal ionization mass spectrometer–dated samples (in italics). Asterisks show the position of the longitudinal section. B. Simplified longitudinal section (from * to **), Chambers A to D, showing the relative positions of the dated horizons and the associated sediments. Solid lines show those relationships of which we are confident, dashed lines those of which we are less confident, and question marks show those parts of the excavated section that we cannot reconstruct except by inference. Sample 79155 is not directly from the Back Wall Series but fits into the stratigraphy. Two samples do not fit into the cross sections: 76151 was loose in the stone pile behind the Back Wall Series, and 76155 was away from the main body of sediments in the steeply inclined rift of Chamber D. MIS—marine isotope stage.

of infinity). Gascoyne (1980), on finding high ^{230}Th/^{234}U ratios in this sample, suggested that leaching had occurred. We did not find this elevated ratio and conclude that the deposit is as old as indicated. This sample cannot be directly fit into the stratigraphy of the Mid-Cave and Back Wall Series. The older than 600 ka age shows that the underlying mud is at least MIS 15 and may be older. This is the oldest known sediment in the cave.

Sample 63272 is a speleothem block that we collected in 2007 from among the boulders under the lowest clay unit of the Mid-Cave Series in Chamber A, close to the position of Gascoyne and Ford's (1984) sample 77238B. The three subsamples from the topmost layer of the central part, at 490 −12/+14 ka, 490 −13/+15 ka, and 523 −16/+18 ka, are within MIS 13. The first two, replicates from the same subsample, can be amalgamated to reduce the error, giving 490 −9/+10 ka. The sample shows a complex history of events, summarized in Figure 5. The center, which grew in MIS 13, is of laminated, clean calcite that was fractured and slightly dissolved before being surrounded by a detrital layer. A thin layer of flowstone was deposited on top, before a further episode of slight dissolution, which was then overlain by a porous, yellowish evaporitic (and thus unfortunately completely unsuitable for dating) overgrowth. The whole was then buried by laminated clay.

Sample 79155 is a clean white drapery flowstone from a complex on the south wall of Chamber D collected by Gascoyne and recorded as growing close to sample 77230, the lowest of a 3 m sequence of overhanging flowstone and sediments, 1.5–4.6 m above the excavated floor (Gascoyne, 1980; Gascoyne and Ford, 1984). It was alpha dated as older than 350 ka. The outermost layer gave a TIMS date of 467 +17/–15 ka, also from MIS 13. The outer surface (of calcited clay) shows that it once had also been buried in sediment. The presence of these two pieces of MIS 13 flowstone, one on each side of the cave, suggests extensive speleothem deposition during that time.

Gascoyne's sample 77237, from the middle of the Mid-Cave Series, has a simple two-layered structure with clean, laminated calcite growing on a clastic fill. The three samples on the 2-cm-thick lower layer yielded overlapping dates of 391 ± 8 ka, 389 −5/+6 ka, and 381 ± 6 ka (note that for this last date, the high U concentration value for the sample directly on the hiatus suggests some contamination from clastic material). This was followed by a short-lived erosional event, and a further 3 cm of renewed calcite deposition, dated as 372 ± 7 ka. These dates are all within the later part of MIS 11.

We collected sample VC09/1 in 2007 from immediately underneath the large roof fall of the Mid-Cave Series. It is a dirty flowstone that yielded a poor basal date, with high detrital contamination, of 330 ± 12 ka, in MIS 9. This flowstone is cracked in many places, presumably by the fall of the roof block.

Sample 76151, a two-layered flowstone collected by Gascoyne from the loose Stone Pile in Loop Passage, had been alpha dated as older than 350 ka. TIMS dates yielded a MIS 9 date on the lower layer (288 ± 4 ka) and MIS 7 on the upper (202 ± 3 ka), the hiatus representing the period of nondeposition during MIS 8. Although this sample was not in growth position, it provides additional information about the timing of calcite deposition in the cave.

Sample 77151 was a 25-cm-thick multilayered flowstone collected by Gascoyne from the Back Wall Series. The remains were fitted into place (Fig. 6) in Figure 5 of Gascoyne et al. (1983b) (same image as Plate 5 in Gascoyne and Ford, 1984). The basal part, Piece A, is now missing, as is the very top of Piece C (but the top is represented by the top of sample 79150). This

TABLE 1. ISOTOPIC DATA FROM TIMS ANALYSIS

Sample	Age (ka)	Age adj. (ka)	^{238}U (µg/g)	^{232}Th (µg/g)	^{230}Th / ^{234}U	^{230}Th/^{238}U	^{234}U/^{238}U	^{230}Th/^{232}Th	^{234}U/^{238}U (initial)
76155 below hiatus 655B	>600	>600	0.62	0.0002	1.0181 ± 0.0020	1.0708 ± 0.0018	1.0518 ± 0.0015	10055	1.317
76155 above hiatus 655T	>600	>600	0.79	0.006	1.0099 ± 0.0017	1.0344 ± 0.0015	1.0243 ± 0.0011	438	1.248
63272 2 mm below top VC33	523 +18/–16	523 +18/–16	1.58	0.003	1.0060 ± 0.0012	1.0433 ± 0.0011	1.0370 ± 0.0007	1603	1.162
63272 top VC22	490 +15/–13	490 +15/–13	1.72	0.004	1.0023 ± 0.0013	1.0383 ± 0.0013	1.0359 ± 0.0009	1441	1.143
63272 top VC1T	490 +14/–12	490 ± 14/–12	1.63	0.004	1.0032 ± 0.0012	1.0417 ± 0.0012	1.0384 ± 0.0008	1412	1.153
79155 top 955T	467 +17/–15	467 +17/–15	0.14	0.002	1.0205 ± 0.0023	1.1202 ± 0.0024	1.0977 ± 0.0007	193	1.366
77237 base V37 BZ	382 +6/–6	381 +6/–6	2.20	0.021	0.9905 ± 0.0015	1.0537 ± 0.0013	1.0638 ± 0.0012	339	1.188
77237 8 mm from base V37AD	391 +8/–8	391 +8/–8	0.50	0.003	0.9945 ± 0.0019	1.0618 ± 0.0018	1.0677 ± 0.0011	651	1.204
77237 12 mm from base V37BJ	389 +6/–5	389 +6/–5	0.57	0.003	0.9928 ± 0.0013	1.0563 ± 0.0012	1.0639 ± 0.0009	609	1.192
77237 top layer 30 mm from base V37 TL	372 +7/–7	372 +7/–7	0.44	0.001	0.9893 ± 0.0022	1.0583 ± 0.0023	1.0697 ± 0.0008	1369	1.200
Vict09/1 base BWR	340 +7/–7	330 +12/–12	0.41	0.135	0.9569 ± 0.0025	0.9611 ± 0.0024	1.0044 ± 0.0010	9	1.011
76151 2 mm below hiatus 651B	289 +4/–3	288 +4/–4	0.24	0.007	0.9395 ± 0.0020	0.9758 ± 0.0018	1.0386 ± 0.0013	100	1.087
76151 3 mm below top 651T	203 +2/–2	202 +3/–3	0.43	0.023	0.8499 ± 0.0026	0.8743 ± 0.0025	1.0287 ± 0.0012	49	1.051
77151 Piece B base 751BB	313 +9/–8	312 +9/–8	0.39	0.017	0.9511 ± 0.0035	0.9771 ± 0.0033	1.0273 ± 0.0032	69	1.066
77151 Piece B 2 mm below top 751BT	275 +4/–4	275 +4/–4	0.56	0.003	0.9380 ± 0.0026	1.0068 ± 0.0021	1.0734 ± 0.0022	496	1.160
77151 base of Piece C 751CH	239 +2/–2	239 +2/–2	0.48	0.124	0.9139 ± 0.0019	1.0243 ± 0.0019	1.1207 ± 0.0010	119	1.237
77151 top of piece C 751CT	201 +1/–1	200 +1/–1	0.53	0.003	0.8466 ± 0.0016	0.8723 ± 0.0015	1.0303 ± 0.0009	414	1.053
79150 20 mm below hiatus V50PH	300 +4/–4	297 +6/–6	0.26	0.030	0.9446 ± 0.0022	0.9730 ± 0.0022	1.0301 ± 0.0009	26	1.070
79150 ~10 mm above hiatus V50BM	210 +1/–1	210 +1/–1	0.66	0.003	0.8622 ± 0.0014	0.8981 ± 0.0013	1.0417 ± 0.0011	610	1.075
79150 12 mm below top V50TP	197 +1/–1	197 +1/–1	0.43	0.001	0.8406 ± 0.0013	0.8661 ± 0.0011	1.0304 ± 0.0010	1319	1.053
VCB 4 mm from bone	118.5 +0.5/0.5	118.3 +0.6/–0.6	0.38	0.002	0.6676 ± 0.0014	0.7066 ± 0.0014	1.0583 ± 0.0013	408	1.082
VCB 9 mm from bone	118.5 +0.9/–0.9	118.1 +1.1/–1.1	0.38	0.005	0.6667 ± 0.0028	0.6989 ± 0.0029	1.0484 ± 0.0011	159	1.068
VCB 21 mm from bone	117.4 +0.5/–0.5	116.8 +0.8/–0.8	0.43	0.008	0.6632 ± 0.0016	0.6947 ± 0.0016	1.0474 ± 0.0009	106	1.066

Note: TIMS—thermal ionization mass spectrometry. Ratios are in activity ratios. Errors are 2σ. Age is quoted as the calculated age first and then the age adjusted for detrital contamination using initial ^{230}Th/^{232}Th values and error from typical crustal values (after Cruz et al., 2005). Decay constant values (from Cheng et al., 2000) are $\lambda230 = 9.1577 \times 10^{-6}$ yr^{-1}, $\lambda234 = 2.8263 \times 10^{-6}$ yr^{-1}, and $\lambda238 = 1.55125 \times 10^{-10}$ yr^{-1}.

sample was the focus of an intense alpha dating effort because it was used for an isotopic profile. The TIMS dates are 312 +9/–8 ka and 275 ± 4 ka at the base and top, respectively, of Piece B, the middle piece, both within MIS 9. This is separated by a hiatus from the upper piece, Piece C, dated as 239 ± 2 ka and 200 ± 1 ka, base and top, in MIS 7. The hiatus thus represents MIS 8. The growth rate from the two dates on Piece C (0.45 ± 0.03 k.y./mm) can be used to give an estimate of 191 ± 2 ka for the date of the missing top, 2 cm above the uppermost TIMS date. Similarly the growth rate from the two dates on Piece B (0.54 ± 0.15 k.y./mm) can be used to estimate the date at the base of the missing Piece A as 334 ± 11 ka, still within MIS 9. The TIMS dates on this sample add precision and a greater measure of certainty, but essentially confirm the careful work of Gascoyne.

Sample 79150, also from the McMaster archives, was adjacent to 77151 and is equivalent to Piece C and a little of Piece B. A subsample near the top yielded a date of 197 ± 1 ka. The second subsample, taken from the clean layers just above the obvious hiatus, yielded a date of 210 ± 1 ka. Both these dates are in MIS 7. The material below the hiatus is very vuggy, dirty, and difficult to date. The single date close to the hiatus is 297 ± 6 ka, in MIS 9. The stalagmitic surface that separates MIS 9 calcite from MIS 7 calcite can be matched for both samples 79150 and 77151. Viewing the samples together (Fig. 6), and following the growth lines, elucidates an important feature of flowstone dating that might otherwise not be apparent: the hiatus in sample 79150

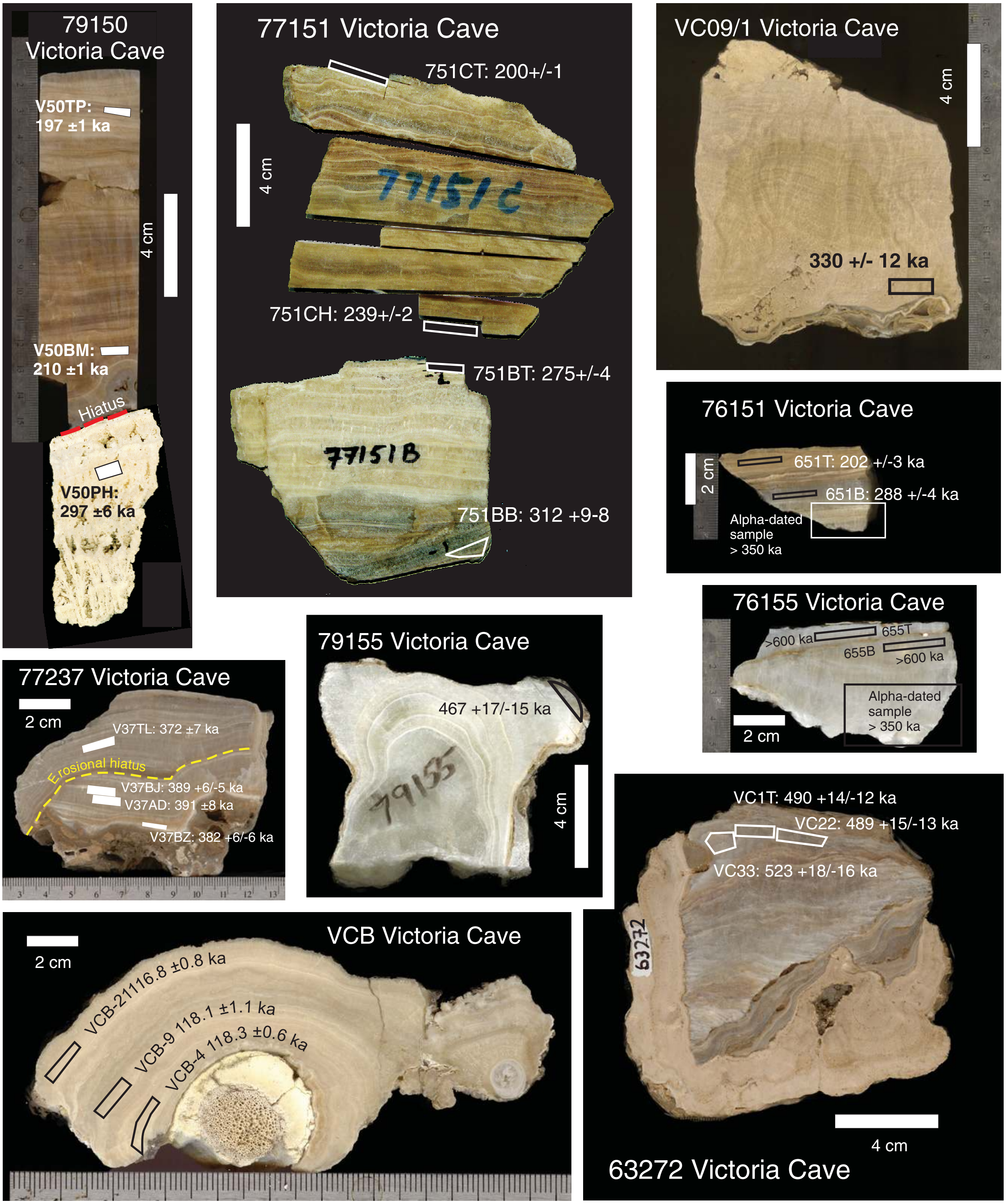


Figure 4. The thermal ionization mass spectrometer–dated samples shown at the same scale.

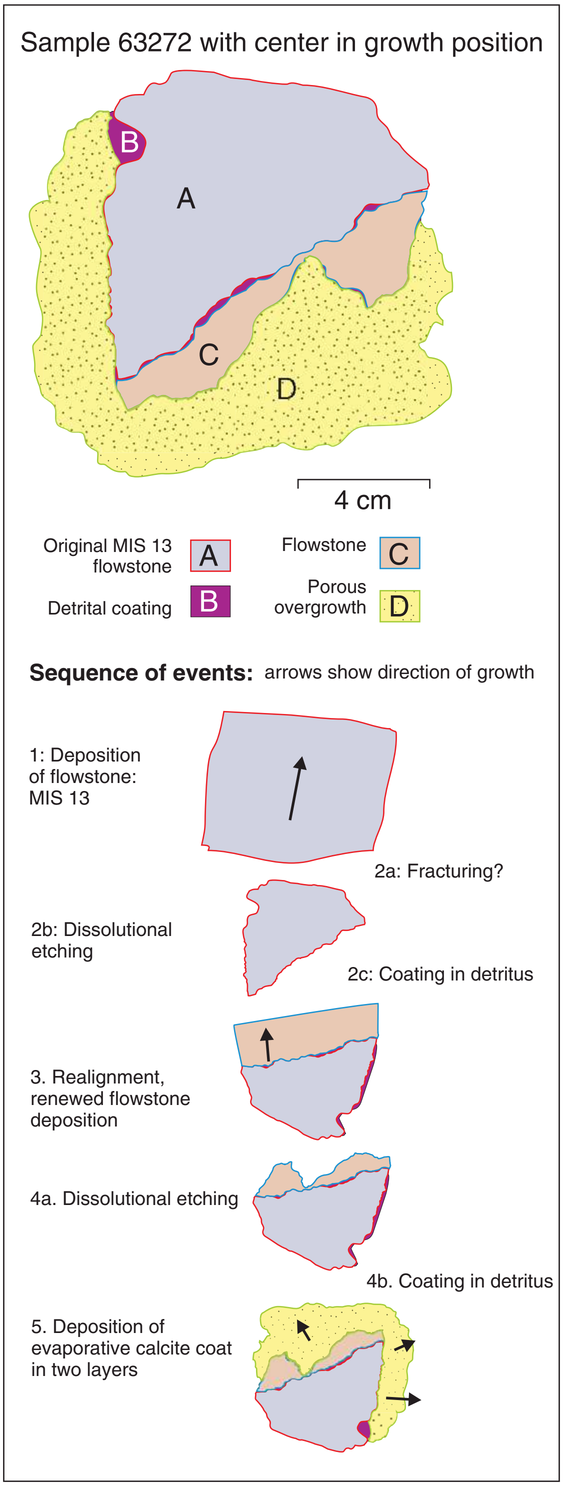


Figure 5. Sequence of events indicated from internal stratigraphy of sample 63272. MIS—marine isotope stage.

is of much longer apparent duration than that in sample 77151. This is caused because the surface depressions must be infilled first and the hiatus in Sample 77150 happens to be an upstanding part. Thus the early part of MIS 7 calcite is missing from sample 77150.

The last sample that we dated was VCB, ~2.5 cm of calcite encasing part of a Red Deer antler (*Cervus elaphus*) from the MIS 5 bone bed in the Back Wall Series. Three layers were dated: the outermost date 21 mm from the bone is 116.8 ± 0.8 ka, the next, 9 mm from the bone, is 118.1 ± 1.1 ka, the third, 4 mm from the bone, is 118.3 ± 0.6 ka.

Pleistocene Timeline

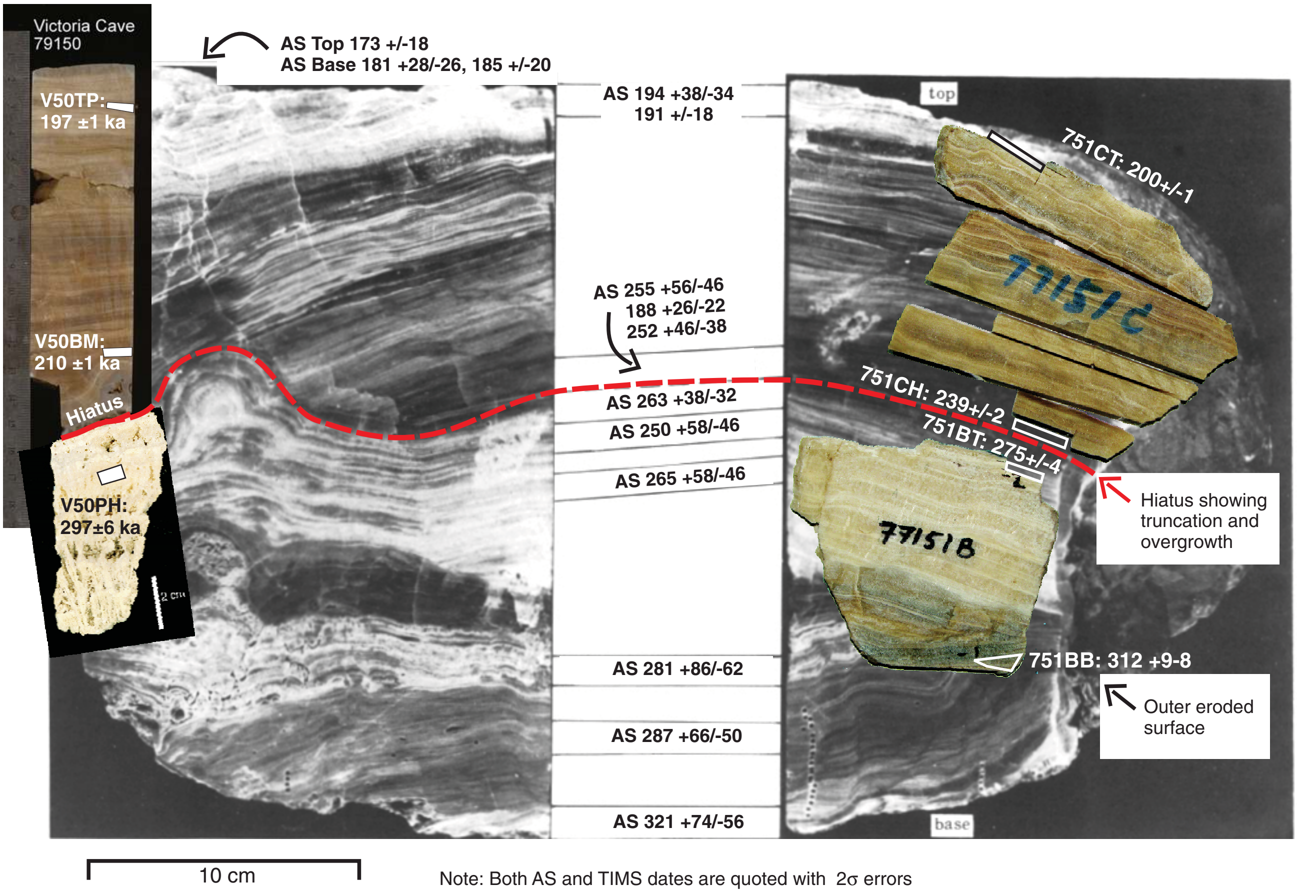
The dates are plotted in Figure 7 with the marine isotope curve for the late Pleistocene from Bassinot et al. (1994). They demonstrate calcite deposition during each of the interglacial periods from MIS 5 to MIS 13 and, possibly, MIS 15. The four intervening clay deposits therefore belong to MIS 12, MIS 10, MIS 6, and MIS 2 (the latter having been dated by ^{14}C on bones; Lord et al., 2007).

Clay Units

The new TIMS dates provide a framework into which the sedimentary stratigraphy must be fit, and stimulated further field observations on the nature of the clays and further archival research into the original field descriptions.

There has been no consensus in the literature about the descriptions and key words to designate each clay unit. Since all the clays are laminated, their distinctive features are of texture and color. Tiddeman's original descriptions (from 1873 to 1879) were extremely detailed, but lacked a consistent overview. In particular, Tiddeman conflated all dark colored clays. Gascoyne (1980) used slightly modified terms for the same units. A significant result of our new dates and field observations is that we can now resolve Tiddeman's "Dark Laminated Clay" into two distinct units separated by dated flowstones.

For our new stratigraphy of the clay units we use Tiddeman's original descriptors as far as possible, picking out the most important distinctive feature for each unit, and giving a different descriptor for each unit. Our designation is, from youngest to oldest: (1) Brown Laminated Clay: MIS 2 (the "Upper Laminated clays" of Tiddeman and Gascoyne); (2) Black Laminated Clay: MIS 6 (part of Tiddeman's "Lower Laminated clays"); (3) Dark brown Waxy Laminated Clay: MIS 10 (the "chocolate brown" clay of Gascoyne, part of Tiddeman's "Lower Laminated clays"); and (4) Light brown Sandy Laminated Clay: MIS 12 (the lower "yellow-brown



Note: Both AS and TIMS dates are quoted with 2σ errors

Figure 6. Samples 77151 and 79150 placed in position relative to the original complete sample (modified from Fig. 5 of Gascoyne et al., 1983b). The marine isotope stage (MIS) 9 to MIS 7 hiatus is shown as the thick dashed line. The original alpha-spectrometric (AS) dates are shown down the center, and the thermal ionization mass spectrometer (TIMS) dates are shown beside each subsample.

laminated clay" of Gascoyne). These designations are shown in Figures 3B and 7.

Sedimentary Stratigraphy

Incorporating the four clays and the five flowstones into the rest of the stratigraphy produces a new sedimentary sequence from youngest to oldest, shown in Table 2. (Note that our dates are not relevant to, and thus offer no new insight into, the Entrance Series, details of which were published; see Murphy and Lord, 2003; Lord et al., 2007.)

Our study of archival documents (i.e., Tiddeman's reports from 1873–1879; the cave excavation records kept by Jackson from 1870 and 1875–1878; and the records of T. Lord from 1937) allowed us to reconstruct many of the details of the stratigraphic relations that are no longer apparent in the field. For example, Tiddeman's fourth report (1877, p. 116) described the contact of the MIS 12 Light brown Sandy Laminated Clay with the MIS 11 calcite and with the MIS 10 Dark brown Waxy Laminated Clay: "There is one point about this light-brown laminated clay which is of much interest: channels appear to have been formed in it. The thin overlying stalagmite appears to have made a thin coating over their walls simultaneous with the like formation on the flatter surfaces between them. The overlying dark waxy clay…is seen to dip into these cavities."

In another example, Tiddeman (1878a, p. 216) reported the finding of canid teeth "resting on the surface" of the sandy laminated clay and at the foot of the dark waxy clay. Descriptions such as these form the basis for the details of Figure 8, along with recent field work.

Speleothem formation was widespread during MIS 9 and 7: the flowstone can still be traced laterally as far as the back of Chamber C (confirmed by two MIS 7 dates from Gascoyne, 1980, at the back of Chamber B). These flowstones were anciently fractured by roof fall events, possibly during early MIS 6 (MIS 5e bones are interspersed among, but not underneath, the blocks). The Black Laminated Clay overlying fractured MIS 7 flowstone to the north of our section against the back wall very nearly fills the cave to the roof. In the line of our section it pinches out (either because it was not deposited or has been eroded away since deposition) and the MIS 5e bone bed in places directly overlies the upper surface of the MIS 7 flowstone.

Archive sources including photographs have been used to reconstruct details of the 1937 excavations that found the MIS 5e bone bed partly encrusted and overlain by thin flowstone close to the back wall of the cave. We still have this material (TIMS dated from 118 to 114 ka), but none is left in the field. The largest piece of archived flowstone encrusting the bone bed collected during this work is ~10 cm thick. It is possible that this flowstone, found in 1937, was part of a more extensive flowstone deposit encountered during the 1870s excavations. Jackson (in his 1875 excavation register) illustrated a section showing a continuous flowstone, ~30 cm thick and anciently fractured, that had formed above the MIS 5e bone bed ~5 m in front of the back wall (see following discussion of the flowstone encrusting the MIS 5e bone bed).

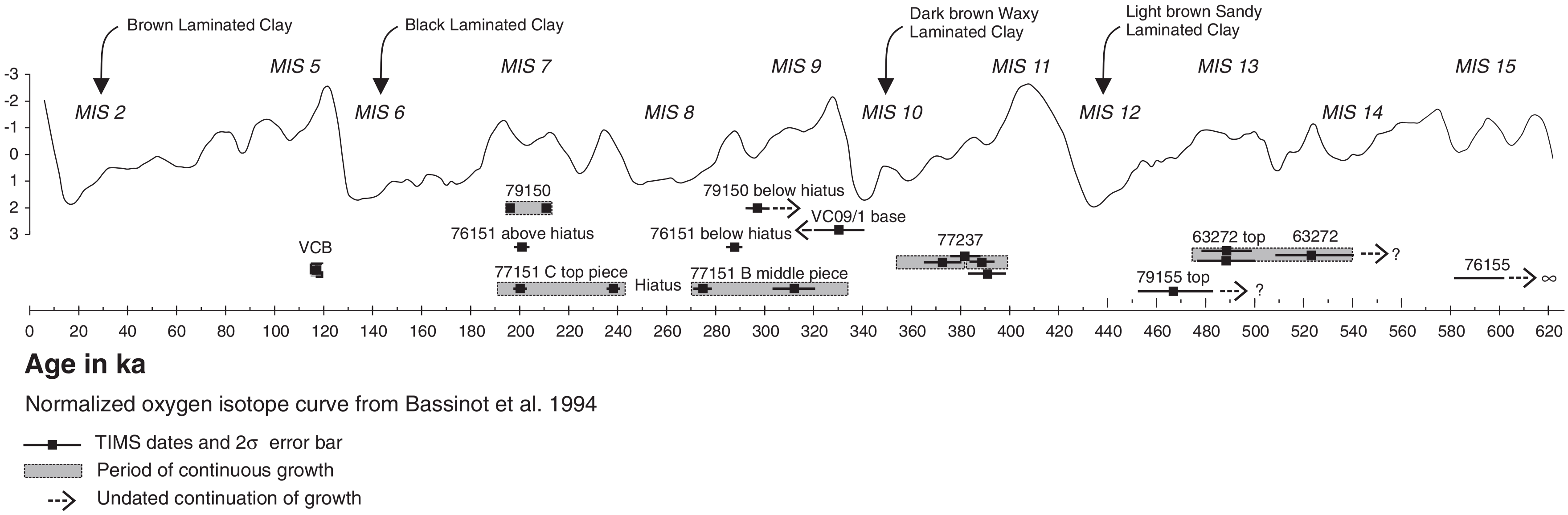


Figure 7. The thermal ionization mass spectrometer (TIMS) dates with 2σ error bars plotted with the marine isotopic curve (MIS) from Bassinot et al. (1994). The arrows show where growth continued beyond the dated horizon. The gray rectangles indicate the start and end of continuous growth in a single sample as estimated from growth rates.

TABLE 2. NEW SEDIMENTARY STRATIGRAPHY FOR VICTORIA CAVE, NORTH YORKSHIRE, UK

Holocene flowstone
Late Glacial bone bed and upper cave earth clastic sediments
MIS 2 Brown Laminated Clay
Late MIS 5(?) Flowstone
MIS 5e Flowstone
MIS 5e Bone bed and lower cave earth clastic sediments
MIS 6 Black Laminated Clay
MIS 7 Flowstone
MIS 8 Hiatus; no flowstone or sediments
MIS 9 Flowstone
MIS 10 Dark brown Waxy Laminated Clay
MIS 11 Flowstone
MIS 12 Light brown Sandy Laminated Clay
MIS 13 Flowstone
Cromerian(?) flowstone
Oldest sediments

Note: MIS–marine isotope stage.

DISCUSSION

Sedimentary Record

Nature and Origin of the Laminated Clays

All the clays have a very distinctive rhythmic fine laminated structure. These thick clays contrast markedly with the more usual pattern of clastic deposition that mostly consists of large roof fall blocks, smaller angular limestone clasts, and some amorphous fine sediment (Tiddeman, 1876a, 1876b). Tiddeman's reports, and modern observation of exposed sections, show that the laminations drape the underlying topography, including fallen roof blocks and drainage channels. No fallen roof blocks are reported from within the laminated clays. In one section the clays filled the cave almost to the roof.

Grain-size analysis of a section of the MIS 2 Brown Laminated Clay (Murphy and Lord, 2003) shows that each unit is made up of light- to dark-colored couplets, the light being coarser and grading up to the finer darker layers (Fig. 9), and that grain size is always <56 µm. Although no rigorous measurement has been done of couplet numbers, a rough estimate suggests that the 3.6 m thickness represents ~1000–2000 couplets. In Murphy and Lord (2003) the chemical composition was reported as largely quartz, with minor amounts of mica, calcite, and some heavy minerals, along with iron-rich clay minerals.

Any theory for the origin of the clays must explain their characteristics (both macroscale and microscale) as well as the sudden input of large quantities of fine clastic sediment and its abrupt cessation. In order to generate undisturbed draping laminations the cave must have been ponded and circulation significantly inhibited. The laminations resemble classic varve deposits in both their form and their association with cold periods. True varves are annual deposits in a lacustrine proximal-glacial environment,

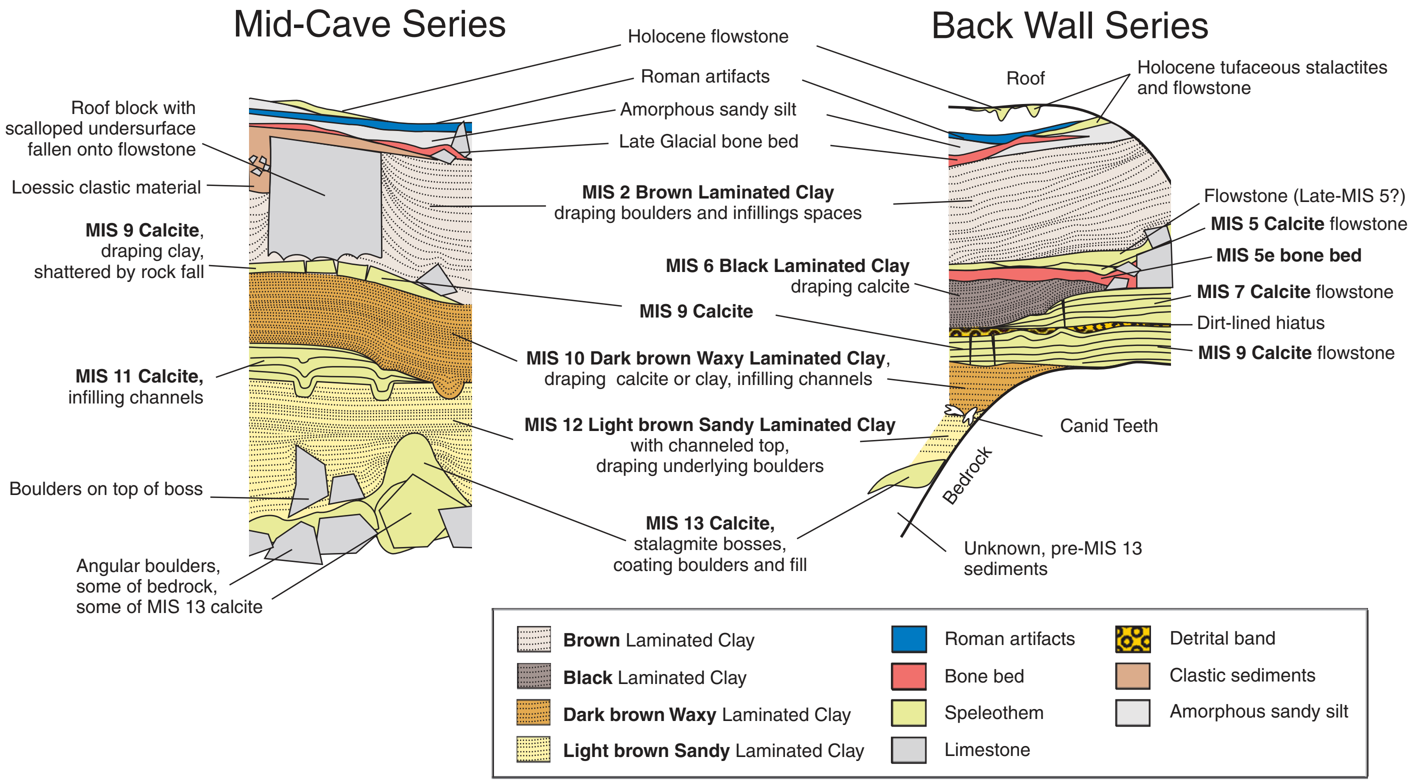


Figure 8. Details of the stratigraphy of the Mid-Cave Series and the Back Wall Series. The color shows the type of sediment and the fine dashed lines show the growth lines or laminations. The laminated clays drape the underlying sediments, sometimes at quite steep angles. MIS—marine isotope stage.

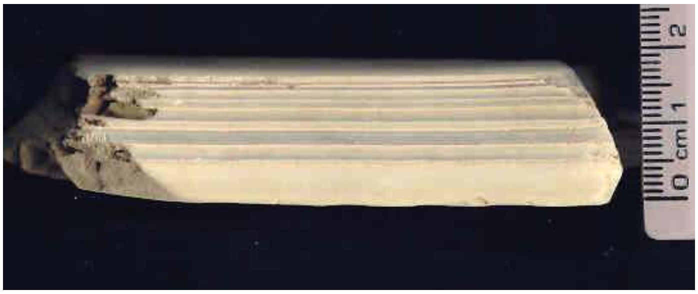


Figure 9. Cross section of part of the marine isotope stage (MIS) 2 Brown Laminated Clay showing the coarser sediment at the base of each couplet, fining up to the darker, finer-grained layers. These are interpreted to represent seasonal variations as in classic varves: the summer melt sends a sediment pulse into the cave, the finer grains settle out during winter.

glacial rock flour and silts being the principal sources of sediment. A similar situation for Victoria Cave would effectively provide both the mechanism for sudden blocking of the drainage and a source of the fine-grained sediment. The location, on the flanks of a glacial valley, is obviously appropriate. That ice overtopped the cave, at least in the LGM, is demonstrated by the distribution of glacial diamict both in the entrance sediments of the cave and in patches locally to an altitude of ~50 m above the cave, the limit of boulder clay reaching 490 m above OD (Arthurton et al., 1988, p. 88).

Glaciolacustrine laminated clays have been reported from only a few caves elsewhere. Valen et al. (1996) reported a series of deposits of laminated clay in the Hamnsundhelleren Cave, western Norway, a cave that is in a very similar situation to Victoria Cave, on the side of a glacial valley. The clays are interpreted as deposition in a subglacial, ice-dammed lake. Like those from Victoria Cave, these clays also harbor no fallen roof blocks, a situation attributed by Valen et al. (1996) to water filling the cave to the roof (presumably from a combination of the absence of frost action and the presence of mechanical support from hydrostatic pressure). The layers of laminated clays separated by bone beds and rock fall events formed as the continental ice sheet expanded and wasted during MIS 3 and MIS 2. In another example, Ward et al. (2003) described 2 m of similar, laminated clays in a raised sea cave, Vancouver Island, Canada, that they also attributed to deposition in a subglacial lake by suspension settling. Audra et al. (2002) described varves in Austrian caves deposited from a suspension of material transported into the caves by subglacial streams, the alternating winter floods and slow summer drainage resulting in light-dark couplets, giving "unquestionable evidence" for past glaciation.

The evidence in Victoria Cave points most strongly to the MIS 2 Brown Laminated Clay being a glaciolacustrine deposit in a speleogenetic setting, the interpretation originally proposed by Tiddeman (1873 and 1876b) and, in a very brief report, by Quin (1997). We consider it unlikely that the laminated clay represents fine sediment carried into the cave on drip waters during periods of marked seasonality in climate, as suggested in Murphy and Lord (2003). Tiddeman's descriptions of a glacial diamict truncating the MIS 5e bone bed at the cave mouth, and his report of finding "several well-glaciated small boulders in the laminated clay itself" (Tiddeman, 1875, p. 135) clearly favor a glacial setting. The interpretation that the MIS 2 clay is of glaciolacustrine origin obviously applies by inference to the other three laminated clays.

Thus the sequence of laminated clays in Victoria Cave provides a record of continental ice expansion in this region during the four glacial maxima of MIS 2, MIS 6, MIS 10, and MIS 12. Furthermore, it suggests that the ice was most probably warm based. The only glacial period not represented in Victoria Cave by laminated clays is MIS 8. This suggests that ice volume during MIS 8 was limited in this region. This is the only site in the north of England where successive glacial maxima can be identified and dated. The value of these old materials preserved inside the cave in a region that otherwise has little direct field evidence of the timing, extent, and nature of pre-Devensian glaciations is high. The information about northwest England is largely limited to Devensian events (Aitkenhead et al., 2002). The tills from earlier glaciations in northeast England lack direct dates, and our understanding of them is further limited by the difficulties of lithological correlation. Catt (2007) only said of the basement tills that they are pre-Ipswichian, and the summary table of evidence from northern England in Aitkenhead et al. (2002, p. 89) is largely free of pre-Ipswichian deposits. The record of dated glacial events from Victoria Cave is therefore significant.

Evidence for Periglaciation

If the copious quantities of laminated clays account for the periods of maximum ice cover, what might be the effect of cold but not glaciated periods? It seems that there is rather limited evidence inside the cave of periglacial activity, but considerable outside. The periglacial activity in the region during the last deglacial period is now well dated. Cosmogenic dates on glacial erratics in the region suggest that the higher ground was deglaciated by ca. 18 ka (Vincent et al., 2010) and optically stimulated luminescence (OSL) dates on surface loess in this region are between 17 and 15 ka (Telfer et al., 2009). Vincent et al. (2010) suggested that scree accumulation in the region also dates to the period 18–14 ka and that the climate was probably cold, dry and windy, i.e., typical periglacial conditions.

Inside the cave the layer of clastic sediments between the MIS 2 Brown Laminated Clays and the Last Interglacial bone bed (Lancaster University Archaeological Unit, 1997; and shown in Fig. 8) are probably periglacial in origin. The fine-grained sand-silt clastic deposit is interpreted as loess that built up at the cave mouth and was redeposited deeper inside the cave (possibly by snowmelt; P. Vincent, 2009, personal commun.). Limestone clasts within this material may originate from freeze-thaw weathering. Cold periods of previous cycles seem to be characterized by rather scanty in-cave deposition, mainly just a little fine clastic material, such as the dirt-lined hiatus between MIS 9 and MIS 7 flowstones, along with roof fall blocks (which are at the base of and on top of the clays, but not within them).

The well-dated evidence for periglacial activity in the region during the last deglacial period suggests, by analogy, that other deglacial periods are likely to have also undergone periglacial conditions. The scarcity of periglacial deposits in the cave during a time when such deposits were frequent outside is likely because the cave was sealed by scree.

A "calcite-cemented, fragmental clay" described by Gascoyne and Ford (1984, p. 80) located directly on the cave floor near to the back wall and under the MIS 9 flowstone layer was previously (tentatively) interpreted as indicating a fairly cold environment. However, subsequent careful field observation has confirmed that this deposit is not a Quaternary deposit at all; rather, it is part of the original depositional fabric of the Carboniferous rock. Mundy and

Lord (1982) noted the presence of several conspicuous paleokarst surfaces within the Goredale Limestone cliff face. The clay underlying the MIS 9 flowstone is simply the remains of a paleokarst clay lining that acted for a time to perch the cave floor and is now apparent as a bench under the sediments (see back wall profile on right side of Fig. 8). It may have been weathered during MIS 10, but was not deposited then and is thus not evidence for in-cave cold period deposition.

Evidence for Periods of Opening and Closing of Cave Entrance

The natural tendency for a cave entrance at the foot of a cliff is to become blocked by scree or by sediment accumulation; it is surprising that the cave is open today (Fig. 10 shows the cave entrance in 1870 before excavation began; the most noticeable feature of the landscape is the apron of scree that just misses Victoria Cave).

We argue for the opening and closing of the cave entrance using the evidence of the types of sediment and faunal records. There appear to be two mechanisms for cave entrance blockage. A scree or sediment pile outside the cave entrance would effectively limit cave access to the larger fauna, so an absence of fauna can be interpreted as a simple restriction of the cave entrance. However, the blockage required to allow the buildup of considerable thickness of laminated clays (in some cases to the cave roof) implies a very effective cessation of drainage. We suggest that blockage simply by scree would not effectively halt drainage and that the laminated clays reflect blockage by glacial ice filling the valley to at least the level of the cave roof at 440 m above OD. Thus we have set up the following simple theory. (1) Laminated sediments indicate lacustrine conditions and thus an entrance blocked to both animals and drainage (MIS 12, MIS 10, MIS 6, and MIS 2). (2) The absence of faunal remains suggests an entrance blocked to animals but not to drainage (MIS 11, MIS 9–7, the later part of MIS 5, MIS 3, and for the Holocene there is little evidence of large mammal and human activity until the Roman period). (3) The presence of faunal remains suggests an open entrance [e.g., Cromerian (?), MIS 5e, Late Glacial Interstadial and Roman period].

For example, the absence in Victoria Cave of elements of the Banwell Bone Cave Mammal Assemblage Zone (MAZ) and Pin Hole MAZ (Currant and Jacobi, 2001) is consistent with the cave being sealed around the end of MIS 5e until late in MIS 2. The presence of the Late Glacial Interstadial bone bed indicates that the cave only became unblocked after the LGM. The limited evidence for Holocene large mammal and human activity suggests that it was largely blocked by accelerated scree formation in the Younger Dryas cold event until it was artificially reopened during the Roman period (Dearne and Lord, 1998). The important implication here is that the record of vertebrate remains in this cave is controlled by geomorphological processes and not simply by composition of the fauna of the region.

Figure 10. An 1870 photograph of the Victoria Cave entrance before excavation began, showing the widespread talus deposits blanketing most of the cliff face.

Removal of the scree pile requires an erosional event. The most common events are likely to be mass movement or glacial scour. In the case of the post-LGM unblocking, the evidence suggests that it is most likely to have been glacial erosion: Tiddeman (1876b) observed that the diamict in the Entrance Series could be seen to truncate and overlay the MIS 5 bone bed. There is no direct evidence of how the cave came to be opened after the formation of the Black Laminated Clay during MIS 6, which permitted the entry of large mammals and spotted hyena occupation during MIS 5e, since there are no deposits at the entrance dating from that time. However, it would be reasonable to assume a similar mechanism to that that happened during MIS 2, especially as deposits of laminated clay formed during both these cold stages in the cave. It therefore seems very likely that the cave was opened by glacial erosion during MIS 6.

The absence of large mammals in Victoria Cave during MIS 11 (at a time when cave bears were denning elsewhere, such as in Kents Cavern; Lundberg and McFarlane, 2007) is indicated by the absence of faunal remains and by the pristine surfaces surviving on the MIS 12 clay. Tiddeman (1877) described in detail the small channels cut into the surface (by post–ice-block drainage) that were neatly lined with calcite or with clay. This surface clearly had no bioturbation, whereas the surfaces of the MIS 6 clay and MIS 2 clay were almost certainly much disturbed by large mammals during MIS 5e and the Late Glacial Interstadial, respectively. It is very likely that the MIS 12 Anglian glaciation scoured the valley, causing valley-side retreat and removal of scree. The absence of large mammals in the cave is most easily explained by a rapid buildup of scree after the glaciation, so that the cave entrance was already blocked before large mammal colonization. Above the LGM glacial diamict in the Entrance Series there was a considerable buildup of scree prior to the Late Glacial Interstadial (Murphy and Lord, 2003), so we might assume a similar, but more intense or longer, period of periglacial weathering after the Anglian. The Anglian, being a more severe glaciation, might have delayed biotic colonization more than the Devensian, so by the time cave bears reached Victoria Cave it was shut.

Evidence for the cave being open in the Cromerian is tentative. It comes from the finding of the two canid teeth (Tiddeman, 1878a). Jackson recorded these in his excavation register for 11 and 12 January 1877 as a "last upper molar of a dog or wolf and a fragment of canine." The teeth (which cannot be located today in any archive) were identified by the paleontologist George Busk and attributed to a small wolf (Tiddeman, 1878a). Tiddeman was clearly aware that the small wolf teeth were much older than the MIS 5e bone bed (1878a), but the finds have never since been commented on despite their obvious significance. A small wolf, *Canis mosbachensis*, is recorded from the Cromerian stratotype at West Runton, Norfolk, and from other early middle Pleistocene sites in Britain and elsewhere in Europe, but does not occur in younger faunal assemblages (Stuart, 1995). It is also found in the early middle Pleistocene cave deposits at Westbury-sub-Mendip (Turner, 1999). The position of these isolated teeth, intercalated between the MIS 12 sandy clay and the MIS 10 dark brown waxy clay, shows only when they were deposited, not when the animal lived (e.g., they may have been reworked and mixed in with the clays when the cave became flooded in MIS 10). However, they indicate that the cave must have been open during the wolf's lifetime for the animal remains to get inside.

Oldest Events: Cromerian and MIS 13

The term Cromerian is used variously: in Britain it has in the past been assumed to represent a single interglacial stage, whereas in the Netherlands the Cromerian Complex includes four interglacials and their intervening cold stages (Preece, 2001; Schreve, 2001; Schreve and Thomas, 2001). An age of MIS 13 is generally agreed upon as the younger limit, but there is no consensus about the age of the start of the Cromerian; Parfitt et al. (2005) proposed at least MIS 17 for the Cromer Forest bed, and by implication, the Cromerian type site at West Runton.

Based on the date from sample 76155 that just straddles the limit of dating at 600 ka, we suggest that the earliest events may be of Cromerian age. Tiddeman (1878) reported that basal blocks could be seen in a few places to overlie water-worn bedrock, and underneath several large bosses of stalagmite. In the sketch in Jackson's cave register for 1 June 1878 (Fig. 11), one of these stalagmite bosses is shown to be almost buried by a later fall of blocks, and subsequently covered by MIS 12 Light brown Sandy Laminated Clay (depicted in Fig. 8 at the base of the Mid-Cave Series). The MIS 13 dated sample 79155 is on top of older sediments (not described by Gascoyne). The MIS 13 dated sample 63272 is one of the fractured blocks on the cave floor and has two stages of post-fracture calcite coating; the outer is evaporitic (Fig. 5). This evaporitic phase suggests significant air flow and that the cave was open to the surface. All of this has to fit in before the advent of the MIS 12 Light brown Sandy Laminated Clays. Based on the MIS 13 age and the position of our two lowest samples, we suggest that the large basal bosses are MIS 13 or early middle Pleistocene in age, but stopped depositing once the chamber became ponded at the start of the clay accretion in MIS 12.

Mid-Cave Record and the Problem of the (Possibly) Phantom Stalagmite Layer

The sequence of clays and calcites is still reasonably well exposed in the Mid-Cave Series (Fig. 12) and at this point our record varies a little from that of Gascoyne. Figure 3b from Gascoyne and Ford (1984) shows the stalagmites sampled for AS U-series dating (redrawn here in Fig. 12A). We have dated the two calcite layers that can be found in situ: our sample VC09/1 (MIS 9), the calcite layer not mentioned by Gascoyne, and Gascoyne's sample 77237 (MIS 11), and we have dated the calcite boulder from the deepest part (our sample 63272, equivalent to Gascoyne's sample 77238B, MIS 13). The distinctive chocolate brown laminated clay (our MIS 10 Dark brown Waxy Laminated Clay) is difficult to mistake and serves as a marker bed. However, Gascoyne's middle layer that includes flowstone sample 77150A (shown ~1 m below the MIS 11 flowstone, with, unfortunately, no indication of the nature of the material that separates the two flowstone layers) is not apparent today. We call it the "phantom" layer because it is also not mentioned in the 1870s excavation records. The section was reexcavated in the 1970s as a series of stepping-back horizontal benches through what are clearly steeply dipping sediments. Thus it is feasible that a contemporaneous but discontinuous layer may appear in the lowest step at the front of the excavation but also in the highest step at the back. It is possible that this mode of excavation caused a misinterpretation of the sequence.

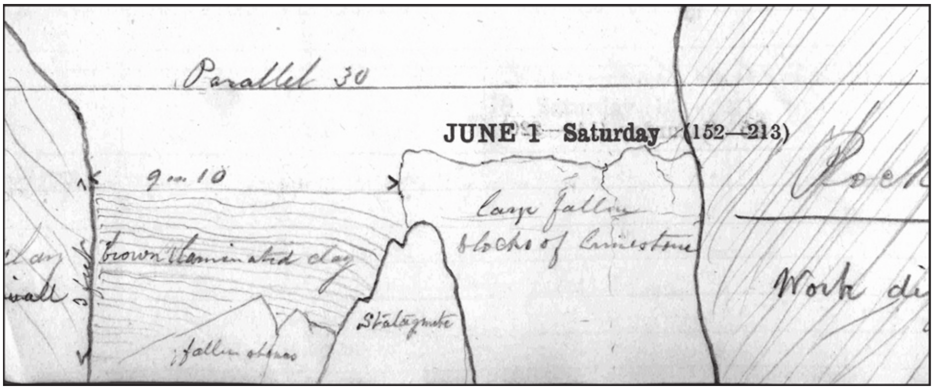


Figure 11. Extract from Jackson's cave register for 1 June 1878 (handwritten excavation register; see text) showing sketch of section where Jackson noted that "fallen stones" and "large fallen blocks of limestone" almost bury the stalagmite boss.

It may not be so simple, however; new information shows that the MIS 11 Hoxnian interglacial period is complex, consisting of at least two warm phases separated by a cold phase, as evidenced at Hoxne, the type site for the Hoxnian in Britain (Ashton et al., 2008). The main Hoxnian interglacial sediments are overlain by the Arctic Bed and then by a later temperate phase. Ocean and ice core isotope data suggest a sharp warming ca. 425 ka, a stable climate until ca. 390 ka, followed by a series of warm-cold oscillations until ca. 360 ka (Bassinot et al., 1994; EPICA Community Members, 2004). Ashton et al. (2008) used amino acid geochronology to redate the later temperate phase of the Hoxne deposits to the late substages of MIS 11. Our dates and the stratigraphy of sample 77237 also fit very well into the late substages of MIS 11 (Fig. 4). Thus the layer that Gascoyne sampled (77150A) might represent the otherwise missing peak MIS 11 calcite, and the unnamed clastic sediments between the two flowstone layers would then correlate with the Arctic Bed stage of the Hoxne sequence. A less likely alternative is that the lower flowstone might represent an event during MIS 12, the Anglian glaciation. The presence of a flowstone horizon within a glaciolacustrine setting would suggest ice retreat and lake drainage during an interstadial event within the Anglian glaciation. Confirmation of this interpretation would inform the current debate about the age of the oldest tills in southern England (Lee et al., 2004), and clearly reexamination of this part of the sequence is needed.

Flowstone Encrusting the MIS 5e Bone Bed

TIMS dates for the bone bed calcite suggest that growth ceased soon after ca. 114 ka (Gilmour et al., 2007). The cessation of growth correlates with the beginning of the C24 cold event in the North Atlantic marine record and the

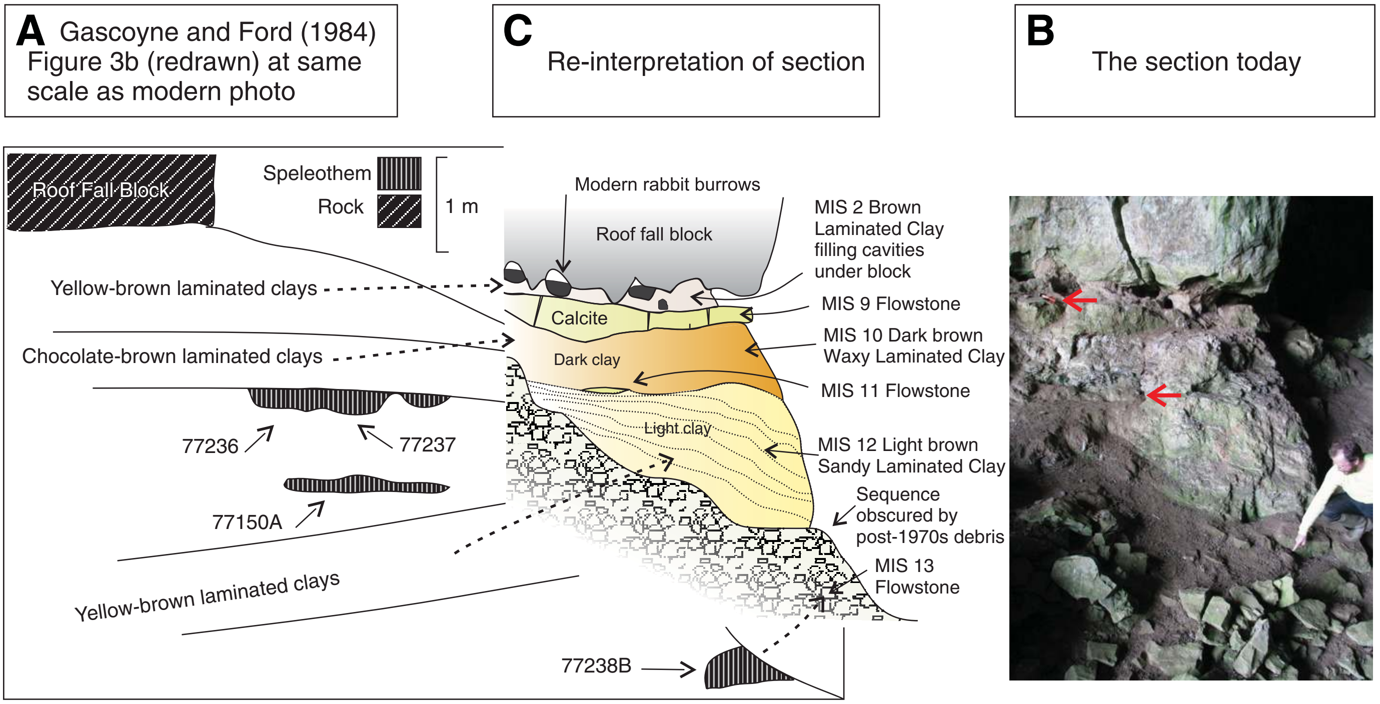


Figure 12. The Mid-Cave Sequence. (A) Redrawn from Figure 3b of Gascoyne and Ford (1984). (B) As it appears in 2007. The red arrows point out the two calcite layers, and the person points to the location of the calcite boulder under the debris. (C) Our reinterpretation of the sequence (C is placed overlapping the blank part of A simply to save space). The marine isotope stage (MIS) 9 calcite layer is cracked, presumably by the fallen roof block. The MIS 2 Brown Laminated Clay has draped the roof fall block and migrated into cavities underneath the block. The MIS 10 Dark brown Laminated Clay is quite clear, as are the draping laminations of the MIS 12 Light brown Sandy Laminated Clay. However, the lower part of the sequence is today covered by debris that has fallen since the 1970s work.

cold and dry Mélisey 1 pollen zone in Europe (Brauer et al., 2007). Resumption of growth is therefore unlikely to be earlier than the end of the C24 event, now very precisely dated to 108.8 ± 1.0 ka (Drysdale et al., 2007). Other examples show a hiatus followed by renewed calcite deposition at that time. Gilmour et al. (2007) dated the start of a major growth phase in a stalagmite overlying a bone bed at Tornewton Cave with a fauna assigned to the Bacon Hole MAZ to 105–98 ka. Flowstones in Kents Cavern also show a hiatus after the MIS 5e growth, with growth resuming ca. 103 ka (Lundberg and McFarlane, 2007). We suspect that Victoria Cave underwent renewed speleothem formation at that time and note that Gascoyne (1980) collected flowstone from high up on back wall that is AS dated to 93 ± 18 ka.

Controls on Speleothem Deposition

Regional Speleothem Deposition

The comparison of speleothem deposition in Victoria Cave to that of other caves in the region is of interest. Calcite deposition requires appropriate conditions of the drip and/or seepage waters and of substrate: the water must not dry up and must be saturated with respect to calcite; the substrate must be stable and not under water. The apparent absence of calcite during the warm MIS 5e peak (at least over the bone bed) is puzzling. We have abundant evidence in the bone bed, with many large herbivorous and grazing mammals, for a very productive ecosystem (Gascoyne et al., 1981). The presence of hippopotamus indicates that winters must have been mild. This suggests lots of soil and plants, adequate rainfall, and high CO_2 groundwater levels. The presence of the animals suggests that the cave was not flooded, at least for some of the year. The paradox at Victoria Cave is the lack of calcite growth during the peak phase of the interglacial, while growth starts late in the interglacial when we know winter temperatures have lowered. Meyer et al. (2006) explained isotopic shifts in an alpine speleothem as indicative of much greater winter cooling relative to summer temperatures going into MIS 5d.

Lancaster Hole, only ~25 km northwest of Victoria Cave (Fig. 1), and Stump Cross Cave, ~25 km southeast, ought to have largely the same climatic history as Victoria Cave and might be expected to share speleothem depositional history. Baker et al. (1995) found that speleothem growth in Lancaster Hole has a distinct relationship with insolation: calcite grew only during brief intervals that correlate with peaks of insolation (at least in the one section that was studied, ca. 140–30 ka). Baker et al. (1996) then compared the timing of speleothem growth in Lancaster Hole with Stump Cross Cave (but from AS dates only). The younger growth periods were agreed by Baker et al. (1996) to coincide well in both caves, but the sample from Stump Cross Cave showed no growth at all during any part of the last interglacial. This was explained, on the basis of the presence elsewhere in the cave of MIS 5 calcite together with detritus on the flowstone, as suggestive of local flooding of the passage at that time.

Victoria Cave is almost equidistant between these two caves, yet our dates from Victoria Cave indicate that the triggers on speleothem growth are quite unlike those of Lancaster Hole (we cannot compare directly with Stump Cross because the periods studied do not coincide). There is no simple relationship with peak insolation. The general tendency is for growth during interglacial periods, but, while the detailed dating has not yet been done to establish the precise limits of onset and cessation of calcite growth in Victoria Cave, the dates we have suggest an absence of calcite during the warmest stages of MIS 5 and MIS 11. Lancaster Hole, although it covers only a small part of the record, is almost exactly opposite, showing precipitation only during the peak warmth of MIS 5. Thus the phases of calcite growth at the Lancaster Hole site, TIMS dated as ca. 129 ka, ca. 103 ka, and ca. 85 ka, are interpreted as peak periods of regional precipitation during MIS 5. The calcite growth phase overlying the MIS 5e bone bed in Victoria Cave, TIMS dated from ca. 118 ka to ca. 114 ka, is clearly out of step with the Lancaster Hole record. In the case of Victoria Cave, the few examples of recent flowstone seem to be undergoing resolution from the modern drips rather than continued deposition. Perhaps high precipitation triggers increased drip waters in Lancaster Hole but a shift to aggressivity of drip waters in Victoria Cave. Both caves record paleohydrological changes, but obviously in different ways. This observed singularity of behavior of caves in close geographical proximity suggests the prudence of careful study of individual systems.

CONCLUSION

The extensive nineteenth century excavations of Victoria Cave provide an opportunity to study deep stratigraphic sequences in different parts of the cave, a situation that is rarely available to modern researchers. We have been able to reconstruct a sequence spanning ~500 k.y. This reconstruction is based on areas of the cave that were most deeply excavated in the 1870s, i.e., Chambers A and D. Chamber B has only been partially excavated and Chamber C only superficially examined (Lord et al., 2007).

The sedimentary sequence for Victoria Cave has been revised and placed into a temporal framework using 23 new TIMS U-Th dates on calcite flowstone from archival material and two newly collected samples. We have used documentary evidence from the original 1870s cave excavation registers and reports, together with the evidence of stratigraphic relationships apparent in the cave today, to produce a new and comprehensive sedimentary profile.

The new framework (shown in the form of a matrix in Fig. 13) clarifies the late Pleistocene history of the cave and the region. The dates reveal that speleothem formation began beyond the range of the dating technique (older than 600 ka). Finite reproducible dates of 490 – 9/+10 ka indicate speleothem deposition during MIS 13, the oldest date we know of for this part of Britain. The sedimentary sequence is thus the longest of any cave in the region. The nearly continuous record of deposition from early middle Pleistocene to Holocene includes calcite flowstone deposition of varying thickness in each of the interglacial stages MIS 13, MIS 11, MIS 9, MIS 7, MIS 5, and MIS 1. It is of interest that the onset of calcite deposition apparently postdates the warmest events of MIS 11 and MIS 5e.

The record also includes four distinct stages of deposition of laminated clays, dated to MIS 12, MIS 10, MIS 6, and MIS 2. This varved clay is interpreted to indicate glaciofluvial deposition in an ice-proximal lacustrine situation when ice advancing up the side of the glacial trough to the level of the cave blocked drainage. The implication is that in this region of northern England, MIS 12, MIS 10, MIS 6, and MIS 2 were the four most extensive glacial periods of the late Pleistocene, and MIS 8 did not have extensive glaciation. Furthermore, it suggests that the ice was warm based for much of the time. This is the most complete record for glacial events in the region; it is the only site where successive glacial maxima can be identified and dated.

The cyclical phases of opening and closing of the cave entrance (that coincide respectively with large faunal remains and laminated clay deposits) follow climatic cycles. The large mammal record indicates that the cave was likely open only for three short periods: possibly an event toward the end of the Cromerian, an event in early MIS 5, and an event in the Late Glacial. The implication is that the faunal record in this cave is constrained by geomorphological processes rather than simply the faunal complement.

In terms of the evolution of the karst landscape of the Yorkshire Dales, this record has confirmed that the phreatic cave was drained long before the Cromerian and certainly before the Anglian glaciation. Gascoyne et al. (1983a)

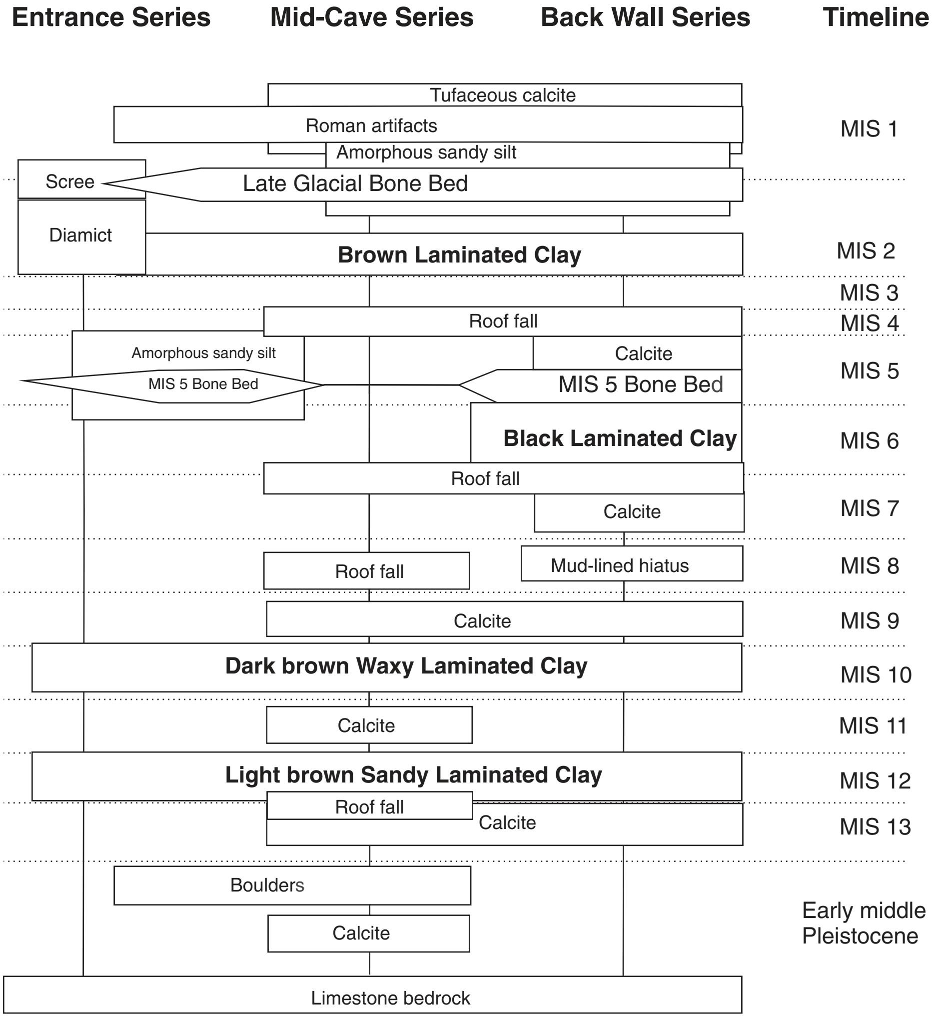


Figure 13. Diagrammatic matrix showing the sedimentary sequence for the three main regions of the cave. The Entrance Series is now just outside the cliff line, but would have been inside before cliff recession in the Late Glacial and Holocene. MIS—marine isotope stage.

proposed a regional uranium best estimate (RUBE) date of 500 ka for initial drainage of the conduit at Victoria Cave and stressed that they considered this a conservative estimate. They suggested that drainage of the conduit could have occurred before 1.5 Ma (Gascoyne and Ford, 1984). The development of the iconic limestone landscape of the Yorkshire Dales is clearly complex and polygenetic in origin.

It is a matter of great concern that these fragile deposits remain largely unprotected and are undergoing rapid and extensive erosion due to visitor damage and rabbit (*Oryctolagus cuniculus*) burrowing. It is ironic that we have this record only because of the endeavors of the nineteenth century excavators. They left the sections open, offering us an unprecedented opportunity for research but coincidentally leaving them open to damage. Victoria Cave is the only such cave that we know of in the region. This site is unique within the Yorkshire Dales National Park and unique within Britain because of its excellent, long stratigraphic sequence.

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